Modular Power Architectures for Microgrid Clusters

Lin, Hengwei; Liu, Leo; Guerrero, Josep M.; Vasquez, Juan Carlos; Dragicevic, Tomislav

Published in:
Proceedings of the 2014 International Conference on Green Energy, ICGE

DOI (link to publication from Publisher):
10.1109/ICGE.2014.6835422

Publication date:
2014

Document Version
Early version, also known as pre-print

Modular Power Architectures for Microgrid Clusters – Invited Paper –

Hengwei Lin[1], Chengxi Liu[1,2], Josep M. Guerrero[1], Juan C. Vasquez[1], and Tomislav Dragicevic[1]

[1] *Institute of Energy Technology - Microgrids Research Programme, Aalborg University, 9220 Aalborg East, Denmark*

[2] *Energinet.dk, Denmark*

Emails: {hwe,cli,joz,juq,tdr}@et.aau.dk

www.microgrids.et.aau.dk

***Abstract*— One of the most important elements in microgrids is the configuration architecture which includes installed capacity, devices location, converter topologies, as well as system control and management strategies. Reliability, security and stability in microgrids require global communication systems in order to provide information for management, supervision, and protection purposes. In this paper, the main objective is to reveal the reasons leading to unreliability and insecurity in microgrids systems, and to propose a generic modular concept which is conceived from the viewpoint of a unified system. The user-frame concept proposed here when designing microgrids considers that the end-user is the basis for the geographical deployment. Meanwhile, a modular user-oriented approach is adopted in order to enhance reliability and expansibility. Finally, a unified dispatching and hierarchical management approach is proposed and evaluated to effectively optimize and manage modular microgrid architectures.**

***Keywords* – Unified dispatching, hierarchical management, user-frame, modular configuration architecture, modular approach.**

I. Introduction

Microgrids are becoming an important concept to integrate distributed generation (DG) units, loads and energy storage systems [1]. However, although nowadays microgrid research is becoming more popular in the literature, still does not play such an important role in the electric power industry. In fact, constraints on reliability, security, stability, and cost are currently the main limiting factor for wider application of microgrids.

At present, one of the most important challenges for both engineers and consumers is the lack of correct and comprehensive understanding about the concept of microgrid. Furthermore, reliability, security, and stability must be ensured, because these are the most important requirements for any electric distribution system, even though these problems may be solved with an obvious cost increase. Although all of these problems make microgrids facing barriers for large-scale deployment in real electrical industry, they still present lots of advantages.

The established concept of microgrids assumes a cluster of loads and microsources that operate as a single controllable system that provides both power and heat to a local area [1]. This concept is quite unclear if we want to analyze the roles, features and functions of microgrids. The lack of a standardized configuration also leads to a serious problem to allocate both DGs and loads. At the same time, the relationship between microgrid and the conventional main power grid is also not clearly standardized. In fact it is only defined that microgrids serve as a controllable source when operating in grid-connected mode. In that sense, communication infrastructure between the microgrid and bulky power grid is critical for timely coordination between distribution network operator and microgrid operator [6]. Microgrids are designed to provide an active coordinative mechanism among users, grid and the microgrid itself, since they conforms an interface between users and the main grid. Besides, all of these requirements on microgrids call for a flexible, reliable, secure and stable system [3], [5], [11].

Meanwhile, a lot of technical drawbacks have been solved from the viewpoint of individual components, e.g. power sharing [8]-[9], power dispatching [7], and harmonics sharing and mitigation [2], [13]-[18]. However, high quality solutions in that sense may lead to inefficient operation and management of microgrids, with an obvious increase of the cost.

The paper is organized as follows. Section II presents the roots of unreliability and insecurity in microgrids. Section III presents a *user-frame* concept to conceive microgrids. In line with that a modular architecture is proposed to achieve flexible capabilities and to ensure reliability. The respective architecture allows plug-and-play functionality, which can play an important role on power dispatching and ancillary services provided by microgrids due to their controllable reconfiguration. In Section IV, a management strategy, named *unified dispatching* and *hierarchical management*, is provided depending on the abovementioned network. Furthermore, smart-grid ready devices such as smart-switches and smart-electricity-meters are evaluated. It is shown that reliability may be ensured depending on the hierarchical modular architecture. Finally, Section V gives the conclusion.

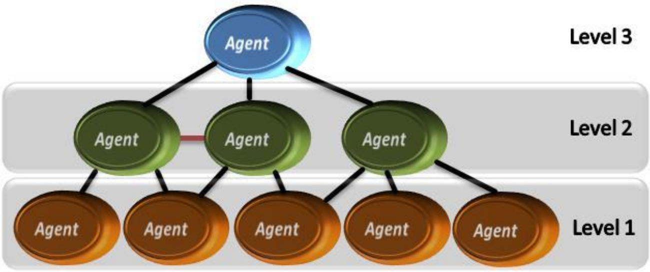

Fig.1. Simple diagram of hierarchical communication system with agents.

II. Reasons for Lack of Reliability, Security and Stability

In this Section, the main reasons that may lead to deterioration of reliability, security and stability in microgrids are described.

A. *Modular Configuration Architecture*

Configuration architecture is one of the most important aspects in microgrids [21], [22]. It determines the installed capacity, devices location, interaction with the bulk power grid, as well as system control and management strategies. However, to the best knowledge of the authors, only a few references paid attention to the architecture from the viewpoint of a unified system. A disordered architecture may result in inefficient control and management strategies. A reasonable architecture in this sense can also improve the reliability and security of the whole system. To enhance the expandability and reliability, while controlling cost, modular approaches can be adopted in microgrids [2]-[4]. This issue will be discussed in Section III in more detail.

B. *Information Technologies*

Reliability, security and stability of the whole system require a global communication system to provide information for management, monitoring, and protection subsets as an in classical Energy Management System (EMS). Communication system plays a key role in a smart and automatic microgrid. Usually, the smarter or the more automatic a microgrid is, the more complex the communication system needs to be. There is a common misunderstanding in microgrids. The communication system does not make microgrid unreliable or affect the plug-and-play capability. The reliability of the system is mainly depending on a reasonable design, backup and redundancy. On the contrary, we can improve these two parts with a suitable communication protocol. International standard IEC 61850 [19] has been widely used in conventional power systems, and which is also foreseen to be a solution to realize flexible integration in microgrids. With a communication protocol, microgrid will become an integrated subsystem of smart grid. Then a more flexible and controllable entity will be achieved [23].

Depending on the geographical location of each microgrid, different communication methodologies can be used. Central communication is more effective for a small scale microgrid or cluster users, since it can collect information very effectively for basic level of a microgrid. It is overwhelmed for a large scale communication, and then the usage of multi-agents may be more appropriated [6]. For a key-node in communication systems, a backup or redundant system can be provided to increase the reliability.

As a key element in smart and automatic microgrids, some requirements are proposed for communication systems.

1) *Reliability*: Since the physical configuration architecture will present a hierarchical/multilevel structure, the communication system also needs to keep a hierarchical model to ensure the reliability and security. A multilayer structure presents good reliability, since it will not be affected by the other subsystems in case a single element collapse. The effect of single-fault in a subsystem will be remedied and further limited through a reasonable management and optimization from the global system level perspective. Consequently, robust communication systems are necessary to provide real-time information to the EMS [24], [25].

2) *Building and Performance Costs:* The cost will be increased without a reasonable layout in real industry utilization. However, automated and intelligent mechanisms depend on modern communication technologies, which will bring a brand new field of research of microgrids applications, especially in the information age. The overall cost can be reduced with more automatic and smarter capabilities, even though moderate cost may increase on some individual components [26].

3) *Expansibility and Practicability:* Highly efficient signal transmission calls for flexible, portable and extensible communications. It is an indispensable design element to accommodate different communication topologies and devices from different manufactures. As a consequence, a suitable communication protocol and standard is urgently needed to connect microgrid with bulk power grid, as well as for connection of individual sources within the single microgrid [5].

4) *Independence:* Communication system should still have the abilities to work when there is a fault or even collapse in microgrid. It means that this part will be independent with the main microgrid frame. Every subsystem in communication network should also be able to work independently, since it provides different information and services for different controllers [21]. As an example, simple hierarchical communication architecture is shown in Fig. 1.

C. *Comprehensive EMS*

However, although microgrids can be operated in island mode, they are different from conventional power system. Usually, the power flow in conventional grids is a unidirectional, i.e. from generators to consumers. However, consumers (loads) and generators (DGs) can coexist in the same microgrid site. This means that the capabilities both in EMS of transmission system and distribution management system (DMS) should be integrated properly in a microgrid. The functions of EMS in a microgrid have not been completed up to date to sustain the effective operation, disregarding the unique geographical features of a microgrid. It is more like a simplified scaled-down version that mimics the whole power system in future microgrids [24], [25].

For a certain geographical site, the power flow will be more complicated without a possibility of full order control and management. Power dispatching also faces this problem in the whole system, especially when there is not enough backup or redundancy in islanded mode. This paper proposes a reconfiguration method to achieve power dispatching and to provide special services, while plug-and-play will also play an important role. All of these problems require unified optimization and management, and EMS will have to make decision for risk assessment, network analysis, early warning, fault diagnosis, demand response, power dispatching, etc [26].

D. Multiple Controllers

The system will face a high pressure to accommodate a big number of DGs and loads. It is necessary to provide a simple and effective coordinated control strategy to integrate different DG controllers in the system [7]. In fact, it is recognized that most of the devices in microgrids need a coordinated control system which is able to simultaneously regulate devices such as PV panels, wind turbines, fuel cells, synchronous generators and various protection appliances [27].

E. Backup and Redundancy

Reliability of power supply needs a proper backup and redundancy in the whole system to deal with a fault or emergency. This issue has its origin in uninterruptible power supply systems (UPS) that were starting to connect in parallel in order to have some backup modules to provide hot-swap functionality, this way a module can be replaced without stopping the whole system and some others of redundancy. These configurations where termed parallel redundant UPS systems [28].

F. Power Quality Issues

An important issue in islanded microgrids is the reactive power sharing. What is more, the control strategy should provide a coordinative mode and high stability to achieve a better power sharing. Microgrid is not stiff enough to compensate harmonics existing in the main grid. For its geographical feature, harmonics can be more easily eliminated in the vicinity of harmonic current/voltage source, than simply shared [17], [18]. Consequently, harmonic sharing between DGs is just a last-resort solution in microgrids. Before, these problems were treated as individual components in microgrids, which limit the effective operation and management [8].

The reasons mentioned above limit the reliability, stability and security of microgrids considerably. They lead to cost increase and the main task is their elimination. This paper makes an attempt to achieve this goal by acting on three basic microgrids elements: users, communications and devices. These three elements are interrelated, while the user will play a key-role in microgrids. The relationship among these three elements is shown in Fig. 2. The *user-frame* concept will be more detailed in Section III.

For modern technologies, communication will doubtlessly play a very important role, even in automatic microgrids and future smart-grids. This paper regards microgrid as an automatic and smart entity [29].

III. Microgrid Structure and Capabilities

A conventional microgrid configuration is shown in Fig. 3, including DGs, local loads, ESS, and the eventual connection to the main grid by means of the intelligent bypass switch (IBS), [7]. Nevertheless, this configuration does not illustrate important details of the microgrid. DGs and loads are arranged intricately, while the microgrid is just connected to the grid through a transformer, which assumes that there is a single PCC. The above concept is overwhelmed when we analyze and design a real microgrid to be connected to a real distribution electrical system.

Here, entity relationship (*E-R*) model [10] is adopted to analyze a microgrid which has a hierarchical structure from the network perspective. Since all the DGs and loads belong to different users, users can both be considered the ending (loads) and beginning (DGs) simultaneously in the microgrid. For this special geographical feature, users play important roles in the microgrid.

Moreover, user is the most important component in microgrid, since it contains all the generators and loads and may provide for ancillary services, such as reactive power and harmonics compensation, demand respond, and devices protection [7], [21], [22], [26], [27], [29]. If we ignore users, we will have only the microgrid frame left, i.e. feeders, nodes, protectors, detection devices, etc. Therefore, this paper assumes that microgrid only contains two entities: user and frame. This view can help us understand the users concern and the main features and functions that the frame should contain.

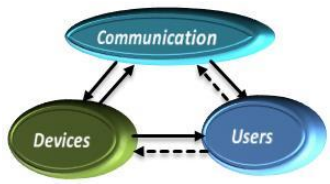

Fig. 2.The relationship among the three elements.

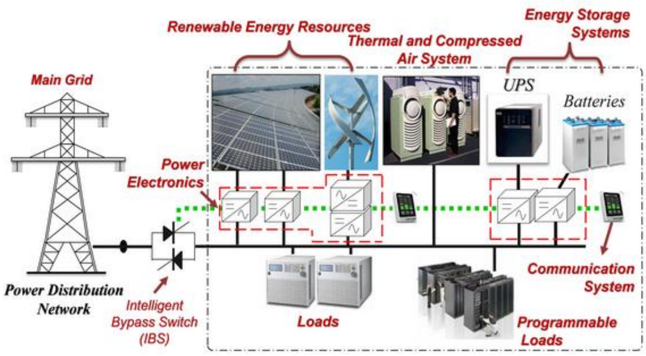

Fig. 3. Conventional microgrid configuration.

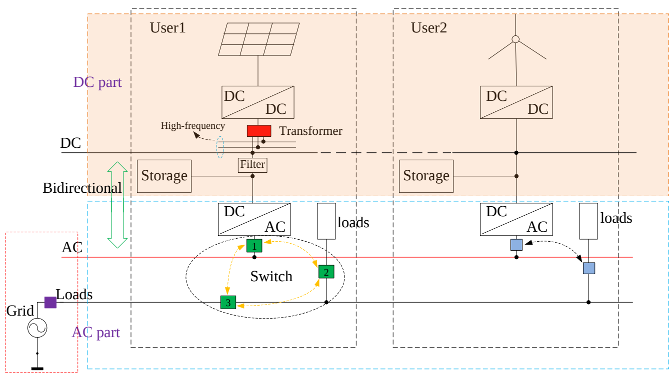

Fig. 4. Diagram of a single user microgrid.

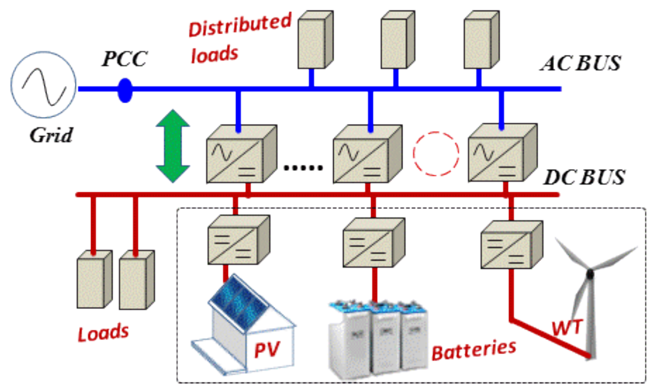

Fig. 5. A simple diagram of multi-bus-microgrid.

A. User Frame

As a most important entity in microgrid, it is necessary to analyze the user role comprehensively. Fig. 4 gives the diagram of single users, where one DG and load belong to a user. The DC bus, noted as red line in Fig. 4, is desired to connect DC appliances, generators and ESS in a more efficient way, see dashed box in Fig. 4. Nevertheless, the whole entity will become a DG cluster or a localized generating plant when including the AC bus, noted as blue line, in the microgrid [2]. How to connect DG clusters to main grid is a problem. Multiple PCCs may exist in a microgrid depending on the physical location.

The relationship among DGs, loads, and the main grid is complex, thus a methodology is proposed here to provide an extra AC bus line/feeder to integrate DGs for the geographical feature in a microgrid. The main purpose is to separate DGs from loads to avoid the harmonics pollution affecting the power source, which also make it possible to eliminate harmonics in the vicinity of the harmonic current/voltage source. Meanwhile, the DGs cluster will have a better robustness to deal with a disturbance in the microgrid. Then, a unified optimization and management framework for microgrids is proposed here to solve problems from a system viewpoint.

Fig. 4 shows the structure of single users. DC-DC converters may produce high-frequency switching voltage/current levels, while high-frequency transformer can be used to get different voltage levels easily. It is necessary to consider whether these DC buses can be connected together, which means that cost will increase due to the use of the extra controllers and devices. However, a multi-bus-microgrid can be conceived to provide various oriented-user services by utilizing the existing DC-bus [22]. What is more, a bidirectional flexible power flow will be necessary between DC and AC buses of the microgrid through different DC-AC converters in order to avoid the circulating power flow shown in Fig. 5, see dashed red line [20].

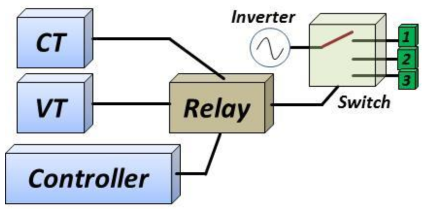

Fig. 6. Configuration of the single-pole multi-throw switch.

The bidirectional power flow control of these elements may provide a possibility to further decrease the energy storage cost that takes up a large proportion of expenditure in microgrid [20].

Plug-and-play is another key feature of microgrids, and it can help us optimize system efficiency and operation [26]. Single-pole multi-throw switchs can be used to protect user's devices, which can be controlled by controllers or users. In Fig. 4, most of inverters are arranged on AC bus line, working in a generation mode. However, the rest of inverters can be arranged on loads/AC bus line to eliminate/compensate the reactive power, harmonics and unbalances thus improving the power quality and, at the same time, they will also act as backup in case of emergency. Through the switches, all the inverters/loads can easily select their operation modes and workplaces depending on the global management system [30]-[32].

The configuration of the single-pole multi-throw switch is shown in Fig. 6, corresponding to the switch shown in Fig. 4. The current transformer (CT) and the voltage transformer (VT) are sensors that monitor the state of the system [30]. When there is a fault, such as an over-current or over-voltage, and has been detected by relevant sensors, the relay will control the switch trip-out [31]. The controller also can manage and update the state of the relay to switch its mode intentionally.

This reconfiguration capability can also be achieved without the AC bus line or single-pole multi-throw switches, since plug-and-play is an inherent feature desirable in microgrids. At the same time, it provides a possibility to solve the contradiction between single-users and system viewpoints [32]. More attention should be paid to meet users' requirements in future microgrids.

B. Microgrid Frame

The microgrid frame is mainly design to ensure that the whole system is operating properly, which may be in a hierarchical and efficient way. In the future, with the presence of large-scale microgrids, it is assumed that the local AC bus between different users will be connected together to form radial AC bus lines [33]-[34].

Fig. 7 shows the diagram of the power dispatching by using "*smart switches*" which are controlled by the EMS [32]. Here the demand response problem can be solved through reconfiguration and adjustments of DGs settings and load shedding/adjustment. We should pointed out that the loads are not allowed to switch in the AC line (DG clusters) in normal situation, since loads are unknown and the harmonics may increase more than expected. However, active loads such as static reactive compensators can be adopted in the system [22].

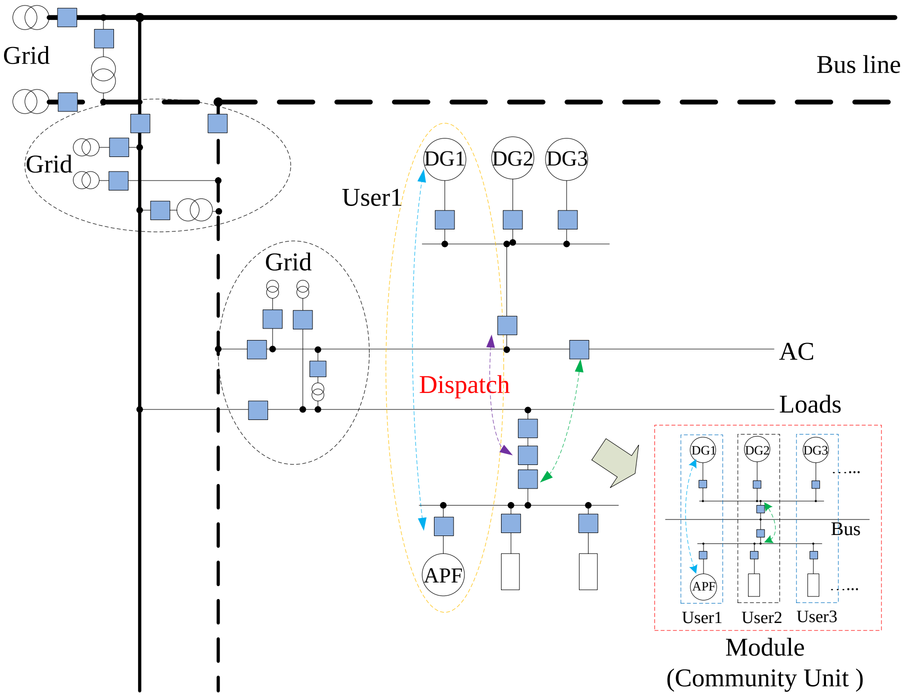

Fig. 7. Diagram of power dispatching through reconfiguration.

DGs clusters may also be switched under discreet consideration. Normally, DG clusters can only be allowed to switch mode to the load line when there is a fault or emergency in the system. We can consider this like a localized islanded portion of network inside the microgrid [22]. It is necessary to further research the influence of the switching model which may bring oscillations and resonances. This reconfiguration function calls for a seamless switching capability.

The form of the frame can be designed differently base on the requirement. A localized AC bus line and connection to grid for several users can also exist in the microgrid. It will become an active module or a cooperative community unit. Compared with the configuration of a conventional microgrid, multiple PCCs will exist in the modular microgrid system approach. In fact, the modular configuration architecture should depend on the scale of local users, since microgrid has a unique geographical feature [34]. The dashed box in Fig. 7 shows an active module for a community unit without connecting the AC/load bus line with other modules. This flexible structure is attractive for reliability, upgrade, expansibility and economy.

From Fig. 4 and Fig. 7, we can see grid permeate in microgrid deeply. It will be difficult to recognize microgrid without AC bus line to separate DGs from loads. When a blackout or fault occurs, the AC bus line will reflect the advantage to ensure high power distribution reliability [11], security and maintainability. Especially when a transmission line calls for repair, there is a risk of blackout or load shedding without AC bus. Meanwhile, AC bus line can reduce the cost of transmission line remodeling for users at present.

However, microgrid also needs support from the main grid, especially when its energy/power capacity is not enough to support the local loads. Moreover, selective automatic load shedding is necessary in order to avoid contingencies [27].

C. *Interactions Between Microgrids and the Main Grid*

Since various services are provided for microgrid itself, it is necessary to which ancillary services microgrid should provide to the main grid. Microgrid faces consumers directly seen from the grid. Normally, there is enough power supplied from the main grid but even though microgrid power generators can share the total amount of supplied power or fully support them. Nevertheless, it is a serious burden for the main grid to accommodate a large scale microgrids clusters [34].

As an example, several large areas blackouts occurred in Denmark, Sweden and North America in 2002-2004, affecting a big amount of consumers. Most of these blackouts were caused by insufficient reactive power sources to support the voltage. To secure the distribution system that closer to the limits without necessary reinforcements, Cell Controller Pilot Project (medium-voltage distribution areas) has been implemented by the Danish TSO *Energinet.dk* [12].

Therefore, when generating electricity, another main goal for microgrids operating in grid-connected mode is to improve for power quality in the vicinity of the harmonic pollution source, which may be mutually beneficial both for microgrid and main grid [18], [22]. To illustrate this, in Fig. 7 an active filter is placed in the load bus in order to improve the power quality, which even works as a backup for emergency. Dispersed installation of active filters on multiple feeders will not cause harmonic propagation or harmonic interference, and it is viable and effective to damp harmonic propagation to mitigate various harmonic pollutions [13]-[16].

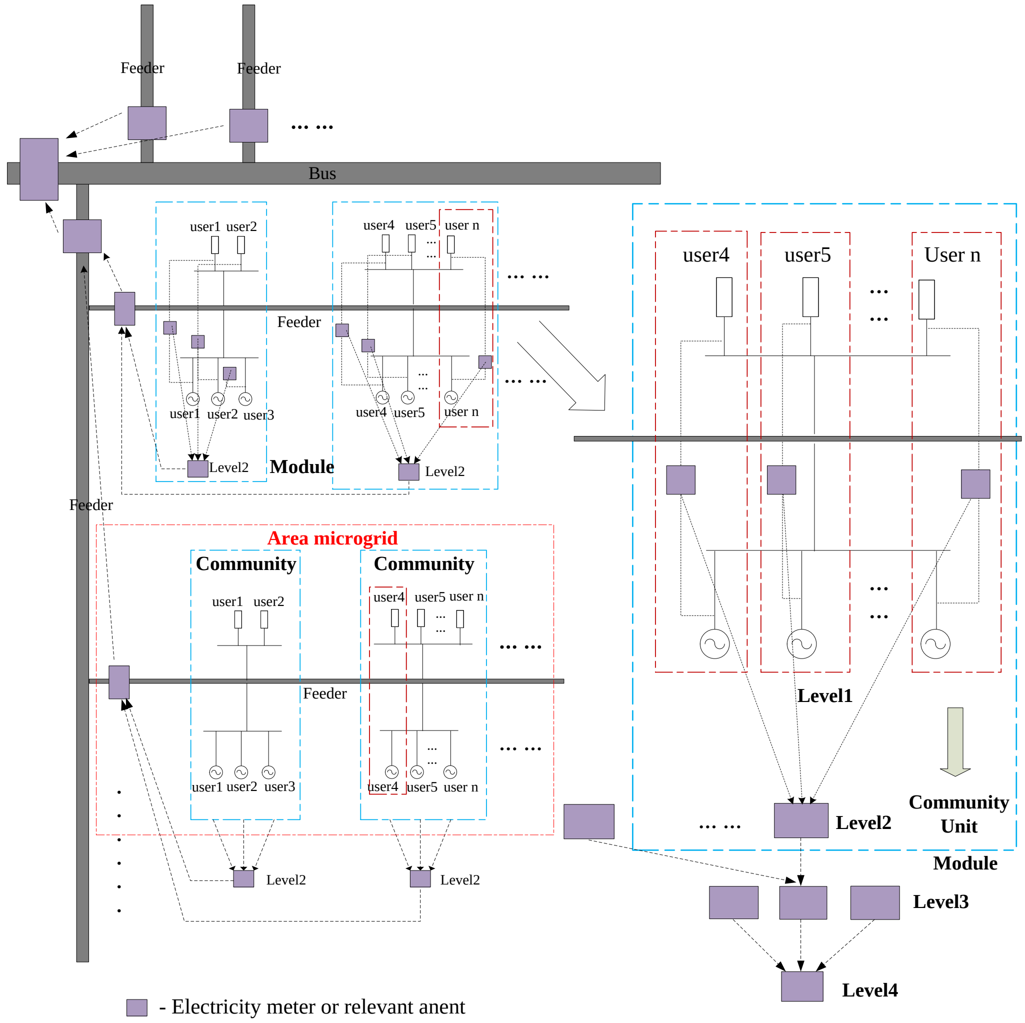

Fig. 8. Multilevel modular configuration architecture in microgrid.

On the other hand, microgrid may also provide electricity in island mode. The higher ambition is aimed at supporting as many loads as possible without external support in the islanded mode in the case of emergencies [29].

IV. Unified Dispatching and Hierarchical Management

The abovementioned microgrid contains multilevel active modules to actively intervene the generation, consumption and operation. The module is self-managed, self-consumption and self-supplied to form an active localized sub-microgrids (sub-networks), which in addition has obviously geographical feature. This modular approach is easy to expand, depending on multilevel users to enhance reliability and reduce cost. One module can exchange power and services with other modules to form the ultimate smart microgrid [21], [27].

A more active participation of the users is integrated to control the cost in this modular structure. From the *User-Frame* concept and modular approach, it is only needed to upgrade the frame for a microgrid project. The other investment can be reduced obviously depending on users. Thus, more attractive policies are urgently required to improve the consumers' and companies' interests and collaboration. Fig. 8 shows the multilevel modular architecture of micrograms.

In microgrids, the distances between different power electronic converters and loads are an important issue. The power line impedance, control signals and electromagnetic-compatibility can be handled under a reasonable design in each module. This method provides a proper environment to connect with other sub-network to form the ultimate system, since most problems are solved locally and promptly. For relative remote modules, it is allowed to cross level to connect with other modules and/or controllers. Compared with other control strategies, droop control reflects a high reliability, since there is a relative weak relationship between DG and its upper controller [21]. It means that DG still has a basic operation capability when there is a fault within the upper controller. The author keeps the vision for future microgrids to modernize the worn infrastructures to form a developed and independent Internet, which depends on modern communication technologies. For users, this may be one of the most important services and attractive points in the coming decades.

A. Protection Devices

In the active module, various protection devices will be adopted to form a protection system, e.g. breaker, fuse, auto reset, sectionalized and relay. The smart switches in Fig. 7 can adopt relay. When there is a fault the relay will disconnect and then send the status to EMS, EMS can also control it through the auxiliary switch. More details about protection for one reliable system can be found in [3].

An effective integration of smart devices and management strategy will ensure a secure and flexible operation in the network. There should be sufficient monitoring and relevant information exchange for microgrid to understand the status. Adaptive relaying, automatic generators/loads shedding and disconnection to localized sub-microgrid will be integrated to deal with the emergency. Moreover, the modular configuration itself has the advantage to isolate and handle most faults locally and promptly.

B. Advanced Metering Infrastructure (AMI)

Smart meter is deemed to be a catalyst for automatic and smart microgrid. The nature of electricity meter is a detection device. To users, they only care about the fee that he/she will charge and the special services from microgrid. Smart meters contain this basic function to calculate the electricity quantity. However, electricity meters can do more for microgrid frame or its module. Much more information can be obtained through electricity meters, such as voltage, current or harmonics. Then the information will be sent to the manager or controller or the upper meter. The node will become visible where the electricity meter is. Meanwhile, the higher the feeder level is, the more capability the meter may have.

Therefore, the smart meters here can detect or calculate all the necessary values in microgrid. Meanwhile, they are able to exchange information with the managers or controllers or other meters. In fact, every big node or bus line needs an electricity meter or other detectors, since it can be seen as a bigger user/module (community unit, local/area microgrid). Then, the network becomes larger and larger. Finally the whole microgrid can be visible. Each level sends the calculated results to the local controller. It will help microgrid become automatic and smart. However, this transmission system should be independent with the main frame of microgrid. It can help us monitor microgrid while it is connecting to the market operator (MO) in grid. This independent configuration is also good for reliability. For users, this method will make charging fees automatically. At the same time, the users can get real-time information from microgrid or grid to play more active roles in the network. The demonstration is shown in Fig. 8.

However, this communication needs additional devices. Most of the meters and communication lines can be defrayed by multilevel modules. Therefore, we just need pay more attention on the frame of microgrid. If microgrids are built and managed modularly, the cost and complexity will be cut. In this sense, companies like Kamstrup in Denmark are promoting smartmeters as a part of a hierarchical AMI global system [35].

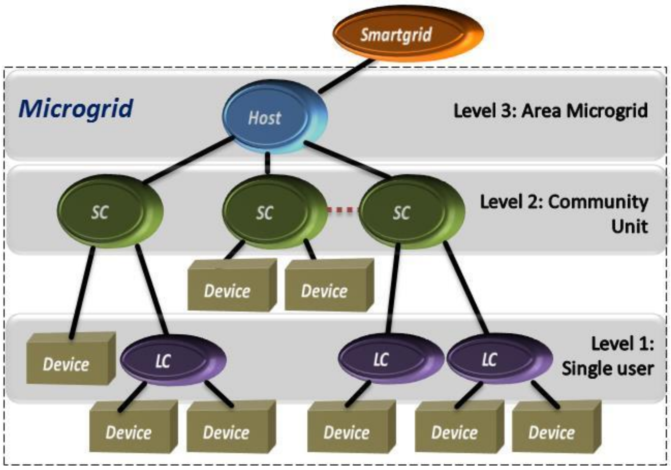

Fig. 9. A hierarchical management system in microgrid.

C. Unified Power Dispatching

EMS should have the capability to calculate and supervise the power flow to face the power demand, while managing the whole network. When there is not enough power from the available DGs, it means loads shedding will be carried out. Through a reasonable loading shedding and backup (e.g. APF on the feeder) enabling, more loads can be reserved in the islanded mode [22]. At the same time, special services for users can also be achieved by reconfiguration.

Fig. 9 shows a hierarchical management in the network. Detectors monitor the local power flow and sent the necessary information to the local controllers of each module. The data will be handled locally, and then they will be sent to its upper level controller. Finally the host controller, here just termed *host*, will calculate these data and get the total power demand. To reduce the quantity of calculation for each controller and to increase the reliability, the detailed dispatching command will also be performed by each module. Consequently, Host only calculates the total power demand for every lower controller (termed *SC* in Fig. 9) and supervises the whole system. Then each *SC* calculates total power demand to local controller (*LC*) and decides the specific dispatching strategy. All the detailed commands are carried out in a modular way, and this management strategy in microgrid is called unified dispatching and hierarchical management (*UDHM*). This modular architecture allows each controller in different levels control devices (*DG*s, loads, and other assets) and the lower controllers simultaneously. Fig. 9 gives the diagram of hierarchical management system.

Modular microgrid has commendable expansibility both horizontally and vertically. It provides flexible reconfiguration capability for emergency while keeping high reliability. At the same time, each level of the configuration architecture is also easy to expand to form a full service subset in the module.

V. CONCLUSION

The reasons that may lead microgrids to unreliable and unsecure operation are given in this paper. The user-frame concept can help us to conceive microgrids, which considers that the user is one of the most important entities in microgrids. Modular architecture microgrids are proposed to assure reliability, expansibility and controlled cost in real electric power industry. Besides, modular microgrids may utilize plug-and-play functionalities to achieve flexible reconfiguration capability which even can be treated as a special service for some consumers. Meanwhile, multilevel users will play important roles in modular microgrids considering geographical location. Unified dispatching and hierarchical management has been evaluated to optimize and manage microgrids from the viewpoint of a whole system. Through a coordinated optimization and management, the reliability and functionality may be improved within a limited cost increasing.

REFERENCES

[1] R. H. Lasseter, "MicroGrids," in *Power Engineering Society Winter Meeting, 2002. IEEE*, 2002, pp. 305-308 vol.1.

[2] M. Prodanovic and T. C. Green, "High-quality power generation through distributed control of a power parkmicrogrid," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1471–1482, Oct. 2006.

[3] T. Kawabata and S. Higashino, "Parallel operation of voltage source inverters," *IEEE Trans. Ind. Appl.*, vol. 24, no. 2, pp. 281–287, Mar. 1988.

[4] J.-F. Chen, C.-L. Chu, and Y.-C. Liou, "Modular parallel three-phaseinverter system," in Proc. ISIE, 1995, pp. 237–242.

[5] Ustun, T.S.; Ozansoy, C.; Zayegh, A., "Modeling of a Centralized Microgrid Protection System and Distributed Energy Resources According to IEC 61850-7-420," *Power Systems, IEEE Transactions on* , vol.27, no.3, pp.1560-1567, Aug. 2012

[6] F. Katiraei, *et al.*, "Microgrids management," *Power and Energy Magazine, IEEE*, vol. 6, pp. 54-65, 2008.

[7] J. M. Guerrero, *et al.*, "Hierarchical control of droop-controlled DC and AC microgrids — a general approach towards standardization," in *Industrial Electronics, 2009. IECON '09. 35th Annual Conference of IEEE*, 2009, pp. 4305-4310.

[8] J. M. Guerrero, *et al.*, "Output Impedance Design of Parallel-Connected UPS Inverters With Wireless Load-Sharing Control," *Industrial Electronics, IEEE Transactions on*, vol. 52, pp. 1126-1135, 2005.

[9] J. M. Guerrero, *et al.*, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *Power Electronics, IEEE Transactions on*, vol. 19, pp. 1205-1213, 2004.

[10] P. P. Chen, "The Entity-Relationship Model -- Toward a Unified View of Data," ACM *Transactions* Database Systems 1.l, pp. 9-36, 1976.

[11] R. S. Balog and P. T. Krein, "Bus Selection in Multibus DC Microgrids," *Power Electronics, IEEE Transactions on*, vol. 26, pp. 860-867, 2011.

[12] P. Lund, "The Danish Cell Project - Part 1: Background and General Approach," in *Power Engineering Society General Meeting, 2007. IEEE*, pp. 1-6, 2007.

[13] H. Akagi, "New trends in active filters for power conditioning,"*Industry Applications, IEEE Transactions on*, vol. 32, pp. 1312-1322, 1996.

[14] H. Akagi, "Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems," *Power Delivery, IEEE Transactions on*, vol. 12, pp. 354-363, 1997.

[15] B. Singh, *et al.*, "A review of active filters for power quality improvement," *Industrial Electronics, IEEE Transactions on*, vol. 46, pp. 960-971, 1999.

[16] L. Gyugyi, "Unified power-flow control concept for flexible AC transmission systems," *Generation, Transmission and Distribution, IEE Proceedings C*, vol. 139, pp. 323-331, 1992.

[17] M. Savaghebi, *et al.*, "Hierarchical control scheme for voltage Harmonics Compensation in an islanded droop-controlled microgrid," in *Power Electronics and Drive Systems (PEDS), 2011 IEEE Ninth International Conference on*, pp. 89-94, 2011.

[18] M. Savaghebi, *et al.*, "Secondary Control Scheme for Voltage Unbalance Compensation in an Islanded Droop-Controlled Microgrid," *Smart Grid, IEEE Transactions on*, vol. 3, pp. 797-807, 2012.

[19] IEC 61850. Communication networks and systems in substations. International Electrotechnical Commission (IEC). Geneva; Switzerland; 2011.

[20] Lu, X.; Guerrero, J.M.; Sun, K.; Vasquez, J.C.; Teodorescu, R.; Huang, L., "Hierarchical Control of Parallel AC-DC Converter Interfaces for Hybrid Microgrids," Smart Grid, IEEE Transactions on , 2014 (in press)

[21] Guerrero, J.M.; Chandorkar, M.; Lee, T.; Loh, P.C., "Advanced Control Architectures for Intelligent Microgrids—Part I: Decentralized and Hierarchical Control," Industrial Electronics, IEEE Transactions on , vol.60, no.4, pp.1254,1262, April 2013

[22] Guerrero, J.M.; Poh Chiang Loh; Tzung-Lin Lee; Chandorkar, M., "Advanced Control Architectures for Intelligent Microgrids—Part II: Power Quality, Energy Storage, and AC/DC Microgrids," Industrial Electronics, IEEE Transactions on , vol.60, no.4, pp.1263,1270, April 2013

[23] Shafiee, Q.; Stefanovic, C.; Dragicevic, T.; Popovski, P.; Vasquez, J.; Guerrero, J., "Robust Networked Control Scheme for Distributed Secondary Control of Islanded MicroGrids," Industrial Electronics, IEEE Transactions on , 2014, Early Access.

[24] Levron, Y.; Guerrero, J.M.; Beck, Y., "Optimal Power Flow in Microgrids With Energy Storage," Power Systems, IEEE Transactions on , vol.28, no.3, pp.3226,3234, Aug. 2013

[25] Dragicevic, T.; Guerrero, J.M.; Vasquez, J.C.; Skrlec, D., "Supervisory Control of an Adaptive-Droop Regulated DC Microgrid With Battery Management Capability," Power Electronics, IEEE Transactions on , vol.29, no.2, pp.695,706, Feb. 2014

[26] Liang Tao; Schwaegerl, C.; Narayanan, S.; Jian Hui Zhang, "From laboratory Microgrid to real markets — Challenges and opportunities," Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on , vol., no., pp.264,271, May 30 2011-June 3 2011

[27] Vandoorn, T.L.; Vasquez, J.C.; De Kooning, J.; Guerrero, J.M.; Vandevelde, L., "Microgrids: Hierarchical Control and an Overview of the Control and Reserve Management Strategies," Industrial Electronics Magazine, IEEE , vol.7, no.4, pp.42,55, Dec. 2013

[28] Guerrero, J.M.; Lijun Hang; Uceda, J., "Control of Distributed Uninterruptible Power Supply Systems," Industrial Electronics, IEEE Transactions on , vol.55, no.8, pp.2845,2859, Aug. 2008

[29] IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems," IEEE Std 1547.4-2011 , vol., no., pp.1,54, July 20 2011

[30] Dewadasa, M.; Ghosh, A.; Ledwich, G., "Protection of microgrids using differential relays," Universities Power Engineering Conference (AUPEC), 2011 21st Australasian , vol., no., pp.1,6, 25-28 Sept. 2011

[31] Lehtla, M.; Rosin, A.; Möller, T.; Pikner, R., "Design of devices for advanced protection, voltage-quality and load priority control in residential microgrids," Power Electronics and Motion Control Conference (EPE/PEMC), 2010 14th International , vol., no., pp.T6-97,T6-100, 6-8 Sept. 2010

[32] Ustun, T.S.; Ozansoy, C.; Zayegh, A., "Differential protection of microgrids with central protection unit support," TENCON Spring Conference, 2013 IEEE , vol., no., pp.15,19, 17-19 April 2013

[33] Ishchenko, D.; Oudalov, A.; Stoupis, J., "Protection coordination in active distribution grids with IEC 61850," Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES , vol., no., pp.1,6, 7-10 May 2012

[34] Yuen, C.; Oudalov, A.; Timbus, A., "The Provision of Frequency Control Reserves From Multiple Microgrids," Industrial Electronics, IEEE Transactions on , vol.58, no.1, pp.173,183, Jan. 2011

[35] Villefrance, R.; Brandt, J.; Eriksen, P.; Jorgensen, H.B., "Smart grid business case for private homes," Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES , vol., no., pp.1,5, 6-9 Oct. 2013